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THE STATUS OF THE STANDARD MODEL

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1 Introduction

In recent years new powerful tests of the Standard Model (SM) have been performed mainly at LEP but also at SLC and at the Tevatron. The running of LEP1 was terminated in 1995 and close-to-final results of the data analysis are now available [1,2]. The experiments at the Z_0 resonance have enormously improved the accuracy in the electroweak neutral current sector. The LEP2 programme is in progress. I went back to my rapporteur talk at the Stanford Conference in August 1989 [3] and I found the following best values quoted there for some of the key quantities of interest for the Standard Model (SM) phenomenology: $m_Z = 91120(160)$ MeV; $m_t = 130(50)$ GeV; $\sin^2\theta_{eff} = 0.23300(230)$; $m_H \gtrsim$ a few GeV and $\alpha_s(m_Z) = 0.110(10)$. Now, after seven years of experimental and theoretical work (in particular with ~ 16 million Z events analysed altogether by the four LEP experiments) the corresponding numbers, as quoted at this Symposium, are: $m_Z = 91186.7(2.0)$ MeV; $m_t = 175.6(5.5)$ GeV; $\sin^2\theta_{eff} = 0.23152(23)$, $m_H \gtrsim 77\ GeV$ and $\alpha_s(m_Z) = 0.119(3)$. Thus the progress is quite evident. The top quark has been at last found and the errors on m_Z and $\sin^2\theta_{eff}$ went down by two and one orders of magnitude respectively. The validity of the SM has been confirmed to a level that we can say was unexpected at the beginning. In the present data there is no significant evidence for departures from the SM, no convincing hint of new physics (also including the first results from LEP2) [4]. The impressive success of the

SM poses strong limitations on the possible forms of new physics. Favoured are models of the Higgs sector and of new physics that preserve the SM structure and only very delicately improve it, as is the case for fundamental Higgs(es) and Supersymmetry. Disfavoured are models with a nearby strong non perturbative regime that almost inevitably would affect the radiative corrections, as for composite Higgs(es) or technicolor and its variants.

2 Status of the Data

The relevant electro-weak data together with their SM values are presented in table 1 [1−2]. The SM predictions correspond to a fit of all the available data (including the directly measured values of m_t and m_W) in terms of m_t, m_H and $\alpha_s(m_Z)$, described later in sect.3, table 4.

Other important derived quantities are, for example, N_ν the number of light neutrinos, obtained from the invisible width: $N_\nu = 2.993(11)$, which shows that only three fermion generations exist with $m_\nu < 45\ GeV$, or the leptonic width Γ_l, averaged over e, μ and τ: $\Gamma_l = 83.91(10) MeV$.

For indicative purposes, in table 1 the "pulls" are also shown, defined as: pull = (data point- fit value)/(error on data point). At a glance we see that the agreement with the SM is quite good. The distribution of the pulls is statistically normal. The presence of a few $\sim 2\sigma$ deviations is what is to be expected. However it is maybe worthwhile to give a closer look at these small discrepancies.

Perhaps the most annoying feature of the data is the persistent difference between the values of $\sin^2\theta_{eff}$ measured at LEP and at SLC. The value of $\sin^2\theta_{eff}$ is obtained from a set of combined asymmetries. From asymmetries one derives the ratio $x = g_V^l/g_A^l$ of the vector and axial vector couplings of the Z_0, averaged over the charged leptons. In turn $\sin^2\theta_{eff}$ is defined by $x = 1 - 4\sin^2\theta_{eff}$. SLD obtains x from the single measurement of A_{LR}, the left-right asymmetry, which requires longitudinally polarized beams. The distribution of the present measurements of $\sin^2\theta_{eff}$ is shown in fig.1. The LEP average, $\sin^2\theta_{eff} = 0.23199(28)$, differs by 2.9σ from the SLD value $\sin^2\theta_{eff} = 0.23055(41)$. The most precise individual measurement at LEP is from A_b^{FB}: the combined LEP error on this quantity is about the same as the SLD error, but the two values are 3.1σ's away. One might attribute this to the fact that the b measurement is more delicate and affected by a complicated systematics. In fact one notices from fig.1 that the value obtained at LEP from A_l^{FB}, the average for l=e, μ and τ, is somewhat low (indeed quite in agreement with the SLD value). However the statement that LEP and SLD agree on leptons while they only disagree when the b quark is considered is not quite right. First, the value of A_e, a quantity essentially identical to A_{LR}, measured at LEP from the angular distribution of the τ polarization, differs by 1.8σ from the SLD value. Second, the low value of $\sin^2\theta_{eff}$ found at LEP from A_l^{FB} turns out to be entirely due to the τ lepton channel which leads to a central value different than that of e and μ [2].The e and μ asymmetries, which are experimentally simpler,

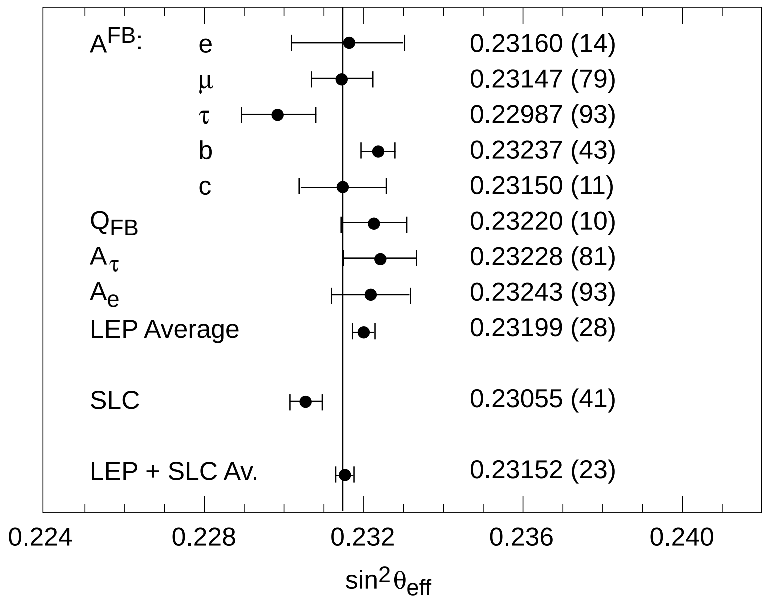

Figure 1: The collected measurements of $\sin^2\theta_{eff}$. The resulting value for the χ^2 is given by $\chi^2/d.o.f = 1.87$. As a consequence the error on the average is enlarged in the text by a factor $\sqrt{1.87}$ with respect to the formal average shown here.

are perfectly on top of the SM fit. Suppose we take only e and μ asymmetries at LEP and disregard the b and τ measurements: the LEP average becomes $\sin^2\theta_{eff} = 0.23184(55)$, which is still 1.9σ away from the SLD value.

In conclusion, it is difficult to find a simple explanation for the SLD-LEP discrepancy on $\sin^2\theta_{eff}$. In view of this, the error on the nominal SLD-LEP average, $\sin^2\theta_{eff} = 0.23152(23)$, should perhaps be enlarged, for example, by a factor $S = \sqrt{\chi^2/N_{df}} \sim 1.4$, according to the recipe adopted by the Particle Data Group in such cases. Accordingly, in the following we will often use the average

$$\sin^2\theta_{eff} = 0.23152 \pm 0.00032 \tag{1}$$

Thus the LEP-SLC discrepancy results in an effective limitation of the experimental precision on $\sin^2\theta_{eff}$. The data-taking by the SLD experiment is still in progress and also at LEP seizable improvements on A_τ and A_b^{FB} are foreseen as soon as the corresponding analyses will be completed. We hope to see the difference to decrease or to be understood.

From the above discussion one may wonder if there is evidence for something special in the τ channel, or equivalently if lepton universality is really supported by the data. Indeed this is the case: the hint of a difference in A_τ^{FB} with respect to the corresponding e and μ asymmetries is not confirmed by the measurements of A_τ and Γ_τ which appear normal[1,2,5]. In principle the fact that an anomaly shows up in A_τ^{FB} and not in A_τ and Γ_τ is not unconceivable because the FB lepton asymmetries are very small and very precisely

Table 1:

Quantity	Data (August '97)	Standard Model Fit	Pull
m_Z (GeV)	91.1867(20)	91.1866	0.0
Γ_Z (GeV)	2.4948(25)	2.4966	-0.7
σ_h (nb)	41.486(53)	41.467	0.4
R_h	20.775(27)	20.756	0.7
R_b	0.2170(9)	0.2158	1.4
R_c	0.1734(48)	0.1723	-0.1
A^l_{FB}	0.0171(10)	0.0162	0.9
A_τ	0.1411(64)	0.1470	-0.9
A_e	0.1399(73)	0.1470	-1.0
A^b_{FB}	0.0983(24)	0.1031	-2.0
A^c_{FB}	0.0739(48)	0.0736	0.0
A_b (SLD direct)	0.900(50)	0.935	-0.7
A_c (SLD direct)	0.650(58)	0.668	-0.3
$\sin^2\theta_{eff}$(LEP-combined)	0.23199(28)	0.23152	1.7
$A_{LR} \to \sin^2\theta_{eff}$	0.23055(41)	0.23152	-2.4
m_W (GeV) (LEP2+p$\bar{p}$)	80.43(8)	80.375	0.7
$1-\frac{m_W^2}{m_Z^2}$ (νN)	0.2254(37)	0.2231	0.6
Q_W (Atomic PV in Cs)	-72.11(93)	-73.20	1.2
m_t (GeV)	175.6(5.5)	173.1	0.4

measured. For example, the extraction of A_τ^{FB} from the data on the angular distribution of τ's could be biased if the imaginary part of the continuum was altered by some non universal new physics effect [6]. But a more trivial experimental problem is at the moment quite plausible.

A similar question can be asked for the b couplings. We have seen that the measured value of A_b^{FB} is about 2σ's below the SM fit. At the same time R_b which used to show a major discrepancy is now only about 1.4σ's away from the SM fit (as a result of the more sophisticated second generation experimental techniques). It is often stated that there is a -2.5σ deviation on the measured value of A_b vs the SM expectation [1,2]. But in fact that depends on how the data are combined. In our opinion one should rather talk of a -1.8σ effect. Let us discuss this point in detail. A_b can be measured directly at SLC by taking advantage of the beam longitudinal polarization. At LEP one measures $A_b^{FB} = 3/4\ A_e A_b$. One can then derive A_b by inserting a value for A_e. The question is what to use for A_e: the LEP value obtained, using lepton universality, from the measurements of A_l^{FB}, A_τ, A_e: $A_e = 0.1461(33)$, or the combination of LEP and SLD etc. The LEP electroweak working group adopts for A_e the SLD+LEP average value which also includes A_{LR} from SLD: $A_e = 0.1505(23)$. This procedure leads to a -2.5σ deviation. However, in this case, the well known $\sim 2\sigma$ discrepancy of A_{LR} with respect to A_e measured at LEP and also to the SM fit, which is not related to the b couplings, further contributes to inflate the number of σ's. Since we are here concerned with the b couplings it is perhaps wiser to obtain A_b from LEP by using the SM value for A_e (that is the pull-zero value of table 1): $A_e^{SM} = 0.1467(16)$.

With the value of A_b derived in this way from LEP we finally obtain

$$A_b = 0.895 \pm 0.022 \qquad (\mathrm{LEP} + \mathrm{SLD}, \mathrm{A_e} = \mathrm{A_e^{SM}} : -1.8) \tag{2}$$

In the SM A_b is so close to 1 because the b quark is almost purely left-handed. A_b only depends on the ratio $r = (g_R/g_L)^2$ which in the SM is small: $r \sim 0.033$. To adequately decrease A_b from its SM value one must increase r by a factor of about 1.6, which appears large for a new physics effect. Also such a large change in x must be compensated by decreasing g_L^2 by a small but fine-tuned amount in order to counterbalance the correponding large positive shift in R_b. In view of this the most likely way out is that A_b^{FB} and A_b have been a bit underestimated at LEP and actually there is no anomaly in the b couplings. Then the LEP value of $\sin^2\theta_{eff}$ would slightly move towards the SLD value, but, as explained above, by far not enough to remove the SLD-LEP discrepancy (for example, if the LEP average for $\sin^2\theta_{eff}$ is computed by moving the central value of A_b^{FB} to the pull-zero value in Table 1 with the same figure for the error, one finds $\sin^2\theta_{eff} = 0.23162(28)$, a value still 2.2σ's away from SLD).

3 Precision Electroweak Data and the Standard Model

For the analysis of electroweak data in the SM one starts from the input parameters: some of them, α, G_F and m_Z, are very well measured, some other ones, $m_{f_{light}}$, m_t and $\alpha_s(m_Z)$ are only approximately determined while m_H is largely unknown. With respect to m_t the situation has much improved since the CDF/D0 direct measurement of the top quark mass[8]. From the input parameters one computes the radiative corrections[7] to a sufficient precision to match the experimental capabilities. Then compares the theoretical predictions and the data for the numerous observables which have been measured, checks the consistency of the theory and derives constraints on m_t, $\alpha_s(m_Z)$ and hopefully also on m_H.

Some comments on the least known of the input parameters are now in order. The only practically relevant terms where precise values of the light quark masses, $m_{f_{light}}$, are needed are those related to the hadronic contribution to the photon vacuum polarization diagrams, that determine $\alpha(m_Z)$. This correction is of order 6%, much larger than the accuracy of a few permil of the precision tests. For some direct experimental evidence on the running of $\alpha(Q^2)$, see ref. [9]. Fortunately, one can use the actual data to in principle solve the related ambiguity. But the leftover uncertainty is still one of the main sources of theoretical error. DAϕNE can in the near future reduce somewhat this error (and also that on the related hadronic contribution to the muon $g-2$ of relevance for the ongoing Brookhaven measurement[10]). In recent years there has been a lot of activity on this subject and a number of independent new estimates of $\alpha(m_Z)$ have appeared in the literature[11],(see also[12]). A consensus has been established and the value used at present is

$$\alpha(m_Z)^{-1} = 128.90 \pm 0.09 \tag{3}$$

As for the strong coupling $\alpha_s(m_Z)$ the world average central value is by now quite

Table 2: Measurements of $\alpha_s(m_Z)$. In parenthesis we indicate if the dominant source of errors is theoretical or experimental. For theoretical ambiguities our personal figure of merit is given.

Measurements	$\alpha_s(m_Z)$	
R_τ	0.122 ± 0.006	(Th)
Deep Inelastic Scattering	0.116 ± 0.005	(Th)
$Y_{\rm decay}$	0.112 ± 0.010	(Th)
Lattice QCD	0.117 ± 0.007	(Th)
$Re^+e^-(\sqrt{s} < 62$ GeV)	0.124 ± 0.021	(Exp)
Fragmentation functions in e^+e^-	0.124 ± 0.012	(Th)
Jets in e^+e^- at and below the Z	0.121 ± 0.008	(Th)
Z line shape (Assuming SM)	0.120 ± 0.004	(Exp)

stable. The error is going down because the dispersion among the different measurements is much smaller in the most recent set of data. The most important determinations of $\alpha_s(m_Z)$ are summarised in table 2 [14]. For all entries, the main sources of error are the theoretical ambiguities which are larger than the experimental errors. The only exception is the measurement from the electroweak precision tests, but only if one assumes that the SM electroweak sector is correct. Our personal views on the theoretical errors are reflected in the table 2. The error on the final average is taken by all authors between ± 0.003 and ± 0.005 depending on how conservative one is. Thus in the following our reference value will be

$$\alpha_s(m_Z) = 0.119 \pm 0.004 \tag{4}$$

Finally a few words on the current status of the direct measurement of m_t. The present combined CDF/D0 result is [8]

$$m_t = 175.6 \pm 5.5\ GeV \tag{5}$$

The error is so small by now that one is approaching a level where a more careful investigation of the effects of colour rearrangement on the determination of m_t is needed. One wants to determine the top quark mass, defined as the invariant mass of its decay products (i.e. b+W+ gluons + γ's). However, due to the need of colour rearrangement, the top quark and its decay products cannot be really isolated from the rest of the event. Some smearing of the mass distribution is induced by this colour crosstalk which involves the decay products of the top, those of the antitop and also the fragments of the incoming (anti)protons. A reliable quantitative computation of the smearing effect on the m_t determination is difficult because of the importance of non perturbative effects. An induced error of the order of a few GeV on m_t is reasonably expected. Thus further progress on the m_t determination demands tackling this problem in more depth.

In order to appreciate the relative importance of the different sources of theoretical errors for precision tests of the SM, I report in table 3 a comparison for the most relevant observables, evaluated using refs. [7,15]. What is important to stress is that the ambiguity from m_t, once by far the largest one, is by now smaller than the error from m_H. We also see from table 3 that the error from $\Delta\alpha(m_Z)$ is expecially important for $\sin^2\theta_{eff}$ and, to a lesser extent, is also sizeable for Γ_Z and ϵ_3.

Table 3: Measurements of $\alpha_s(m_Z)$. In parenthesis we indicate if the dominant source of errors is theoretical or experimental. For theoretical ambiguities our personal figure of merit is given.

Parameter	Δ^{exp}_{now}	$\Delta\alpha^{-1}$	Δ_{th}	Δm_t	Δm_H	$\Delta\alpha_s$
Γ_Z (MeV)	± 2.5	± 0.7	± 0.8	± 1.4	± 4.6	± 1.7
σ_h (pb)	53	1	4.3	3.3	4	17
$R_h \cdot 10^3$	27	4.3	5	2	13.5	20
Γ_l (keV)	100	11	15	55	120	3.5
$A^l_{FB} \cdot 10^4$	10	4.2	1.3	3.3	13	0.18
$\sin^2\theta \cdot 10^4$	$\sim$3.2	2.3	0.8	1.9	7.5	0.1
m_W (MeV)	80	12	9	37	100	2.2
$R_b \cdot 10^4$	9	0.1	1	2.1	0.25	0
$\epsilon_1 \cdot 10^3$	1.2		$\sim$0.1			0.2
$\epsilon_3 \cdot 10^3$	1.4	0.5	$\sim$0.1			0.12
$\epsilon_b \cdot 10^3$	2.1		$\sim$0.1			1

Table 4:

Parameter	LEP(incl.m_W)	All but m_W, m_t	All but m_t	All Data
m_t (GeV)	$158{+}14-11$	$157{+}10-9$	$161{+}10-8$	173.1 ± 5.4
m_H (GeV)	$83{+}168-49$	$41{+}64-21$	$42{+}75-23$	$115{+}116-66$
$log[m_H(GeV)]$	$1.92{+}0.48-0.39$	$1.62{+}0.41-0.31$	$1.63{+}0.44-0.33$	$2.06{+}0.30-0.37$
$\alpha_s(m_Z)$	0.121 ± 0.003	0.120 ± 0.003	0.120 ± 0.003	0.120 ± 0.003
χ^2/dof	8/9	14/12	16/14	17/15

The most important recent advance in the theory of radiative corrections is the calculation of the $o(g^4 m_t^2/m_W^2)$ terms in $\sin^2\theta_{eff}$ and m_W (not yet in $\delta\rho$) [16]. The result implies a small but visible correction to the predicted values but expecially a seizable decrease of the ambiguity from scheme dependence (a typical effect of truncation).

We now discuss fitting the data in the SM. Similar studies based on older sets of data are found in refs. [13]. As the mass of the top quark is finally rather precisely known from CDF and D0 one must distinguish two different types of fits. In one type one wants to answer the question: is m_t from radiative corrections in agreement with the direct measurement at the Tevatron? For answering this interesting but somewhat limited question, one must clearly exclude the CDF/D0 measurement of m_t from the input set of data. Fitting all other data in terms of m_t, m_H and $\alpha_s(m_Z)$ one finds the results shown in the third column of table 4 [2]. Other similar fits where also m_W direct data are left out are shown.

The extracted value of m_t is typically a bit too low. There is a strong correlation between m_t and m_H. $\sin^2\theta_{eff}$ and m_W [17] drive the fit to small values of m_H. Then, at small m_H the widths, drive the fit to small m_t. In this context it is important to remark that fixing m_H at 300 GeV, as was often done in the past, is by now completely obsolete, because it introduces too strong a bias on the fitted value of m_t. The change induced on the fitted value of m_t when moving m_H from 300 to 65 or 1000 GeV is in fact larger than the error on the direct measurement of m_t.

In a more general type of fit, e.g. for determining the overall consistency of the SM or the best present estimate for some quantity, say m_W, one should of course not ignore the existing direct determinations of m_t and m_W. Then, from all the available data, by fitting m_t, m_H and $\alpha_s(m_Z)$ one finds the values shown in the last column of table 4. This is the fit also referred to in table 1. The corresponding fitted values of $\sin^2\theta_{eff}$ and m_W are:

$$\begin{aligned}\sin^2\theta_{eff} &= 0.23152 \pm 0.00022, \\ m_W &= 80.375 \pm 0.030 GeV \end{aligned} \tag{6}$$

The fitted value of $\sin^2\theta_{eff}$ is identical to the LEP+SLD average and the caution on the error expressed in the previous section applies. The error of 30 MeV on m_W clearly sets up a goal for the direct measurement of m_W at LEP2 and the Tevatron.

As a final comment we want to recall that the radiative corrections are functions of $log(m_H)$. It is truly remarkable that the fitted value of $log(m_H)$ is found to fall right into the very narrow allowed window around the value 2 specified by the lower limit from direct searches, $m_H > 77\ GeV$, and the theoretical upper limit in the SM $m_H < 600 - 800\ GeV$ (see sect.6). The fulfilment of this very stringent consistency check is a beautiful argument in favour of a fundamental Higgs (or one with a compositeness scale much above the weak scale).

4 A More General Analysis of Electroweak Data

We now discuss an update of the epsilon analysis [18,19] which is a method to look at the data in a more general context than the SM. The starting point is to isolate from the data that part which is due to the purely weak radiative corrections. In fact the epsilon variables are defined in such a way that they are zero in the approximation when only effects from the SM Λat tree level plus pure QED and pure QCD corrections are taken into account. This very simple version of improved Born approximation is a good first approximation according to the data and is independent of m_t and m_H. In fact the whole m_t and m_H dependence arises from weak loop corrections and therefore is only contained in the epsilon variables. Thus the epsilons are extracted from the data without need of specifying m_t and m_H. But their predicted value in the SM or in any extension of it depend on m_t and m_H. This is to be compared with the competitor method based on the S, T, U variables [21,22]. The latter cannot be obtained from the data without specifying m_t and m_H because they are defined as deviations from the complete SM prediction for specified m_t and m_H. Of course there are very many variables that vanish if pure weak loop corrections are neglected, at least one for each relevant observable. Thus for a useful definition we choose a set of representative observables that are used to parametrize those hot spots of the radiative corrections where new physics effects are most likely to show up. These sensitive weak correction terms include vacuum polarization diagrams which being potentially quadratically divergent are likely to contain all possible non decoupling effects (like the quadratic top quark mass dependence in the SM). There are three independent vacuum polarization contributions. In the same

Table 5: Experimental values of the epsilons in the SM from different sets of data. These values (in 10^{-3} units) are obtained for $\alpha_s(m_Z) = 0.119 \pm 0.003$, $\alpha(m_Z) = 1/128.90 \pm 0.09$, the corresponding uncertainties being included in the quoted errors [19].

ϵ 10^3	Only def. quantities	All asymmetries	All High Energy	All Data
ϵ_1 10^3	4.0 ± 1.2	4.3 ± 1.2	4.1 ± 1.2	3.9 ± 1.2
ϵ_2 10^3	-8.3 ± 2.3	-9.1 ± 2.1	-9.3 ± 2.2	-9.4 ± 2.2
ϵ_3 10^3	2.9 ± 1.9	4.3 ± 1.4	4.1 ± 1.4	3.9 ± 1.4
ϵ_b 10^3	-3.2 ± 2.3	-3.3 ± 2.3	-3.9 ± 2.1	-3.9 ± 2.1

spirit, one must add the $Z \to b\bar{b}$ vertex which also includes a large top mass dependence. Thus altogether we consider four defining observables: one asymmetry, for example A^l_{FB}, (as representative of the set of measurements that lead to the determination of $\sin^2\theta_{eff}$), one width (the leptonic width Γ_l is particularly suitable because it is practically independent of α_s), m_W and R_b. Here lepton universality has been taken for granted, because the data show that it is verified within the present accuracy. The four variables, ϵ_1, ϵ_2, ϵ_3 and ϵ_b are defined in ref. [18] in one to one correspondence with the set of observables A_l^{FB}, Γ_l, m_W, and R_b. The definition is so chosen that the quadratic top mass dependence is only present in ϵ_1 and ϵ_b, while the m_t dependence of ϵ_2 and ϵ_3 is logarithmic. The definition of ϵ_1 and ϵ_3 is specified in terms of A_l^{FB} and Γ_l only. Then adding m_W or R_b one obtains ϵ_2 or ϵ_b. The values of the epsilons as obtained [19], following the specifications of ref. [18], from the defining variables are shown in the first column of table 5.

To proceed further and include other measured observables in the analysis we need to make some dynamical assumptions. The minimum amount of model dependence is introduced by including other purely leptonic quantities at the Z pole such as A_τ, A_e (measured from the angular dependence of the τ polarization) and A_{LR} (measured by SLD). For this step, one is simply assuming that the different leptonic asymmetries are equivalent measurements of $\sin^2\theta_{eff}$ (for an example of a peculiar model where this is not true, see ref. [20]). We add, as usual, the measure of A_b^{FB} because this observable is dominantly sensitive to the leptonic Πvertex. We then use the combined value of $\sin^2\theta_{eff}$ obtained from the whole set of asymmetries measured at LEP and SLC with the error increased according to eq.(1) and the related discussion. At this stage the best values of the epsilons are shown in the second column of table 5. In figs. 2-4 we report the 1σ ellipses in the indicated ϵ_i-ϵ_j planes that correspond to this set of input data. The status of ϵ_b is shown in fig.5. The central value of ϵ_b is shifted with respect to the SM as a consequence of the still imperfect matching of R_b. In fig.5 we also give a graphical representation of the uncertainties due to $\alpha(m_Z)$ and $\alpha_s(m_Z)$.

All observables measured on the Z peak at LEP can be included in the analysis provided that we assume that all deviations from the SM are only contained in vacuum polarization diagrams (without demanding a truncation of the q^2 dependence of the corresponding functions) and/or the $Z \to b\bar{b}$ vertex. From a global fit of the data on m_W, Γ_T, R_h, σ_h, R_b and $\sin^2\theta_{eff}$ (for LEP data, we have taken the correlation matrix for Γ_T, R_h and σ_h given

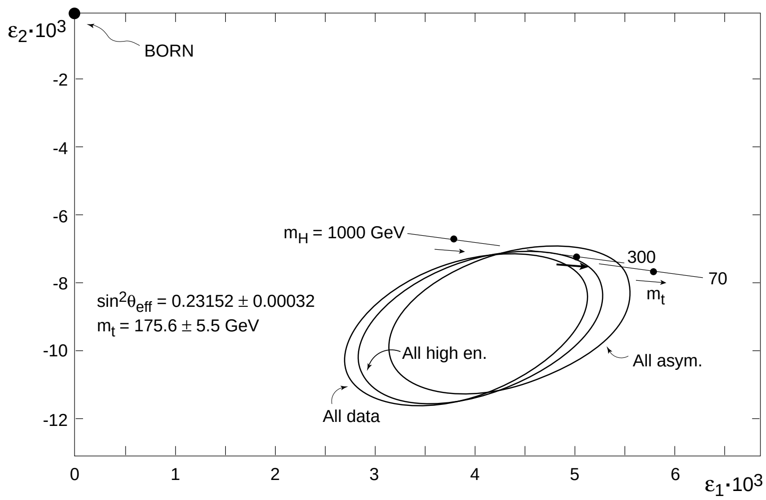

Figure 2: Data vs theory in the ϵ_2-ϵ_1 plane. The origin point corresponds to the "Born" approximation obtained from the SM at tree level plus pure QED and pure QCD corrections. The predictions of the full SM (also including the improvements of ref. [16]) are shown for $m_H = 70$, 300 and 1000 GeV and $m_t = 175.6 \pm 5.5\ GeV$ (a segment for each m_H with the arrow showing the direction of m_t increasing from -1σ to $+1\sigma$). The three $1-\sigma$ ellipses (38% probability contours) are obtained from a) "All Asymm." :Γ_l, m_W and $\sin^2\theta_{eff}$ as obtained from the combined asymmetries (the value and error used are shown); b) "All High En.": the same as in a) plus all the hadronic variables at the Z; c) "All Data": the same as in b) plus the low energy data.

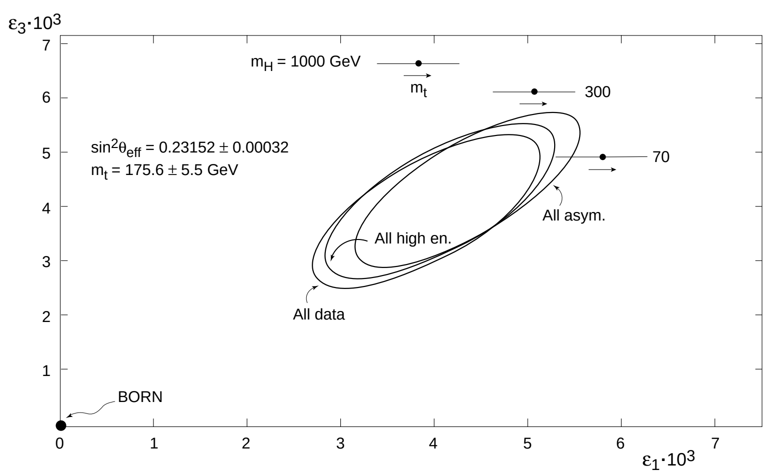

Figure 3: Data vs theory in the ϵ_3-ϵ_1 plane (notations as in fig.2).

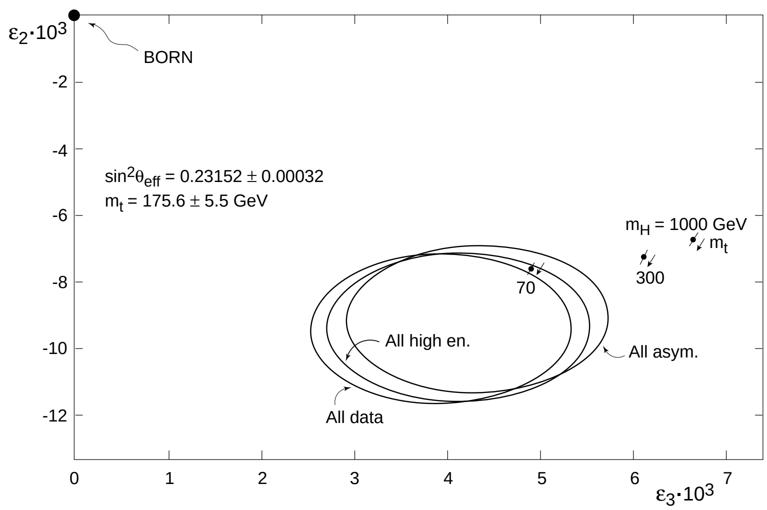

Figure 4: Data vs theory in the ϵ_2-ϵ_3 plane (notations as in fig.2).

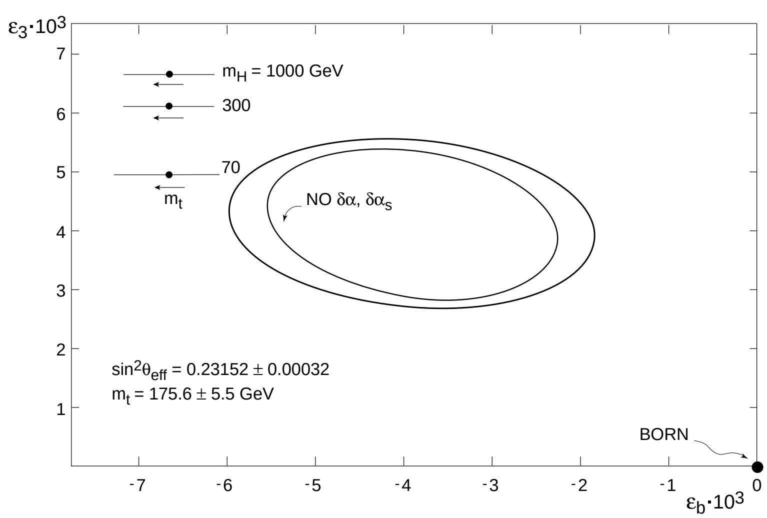

Figure 5: Data vs theory in the ϵ_3-ϵ_b plane (notations as in fig.2, except that both ellipses refer to the case b)) The inner $1-\sigma$ ellipse is without the errors induced by the uncertainties on $\alpha(m_Z)$ and $\alpha_s(m_Z)$.

by the LEP experiments [2], while we have considered the additional information on R_b and $\sin^2\theta_{eff}$ as independent) we obtain the values shown in the third column of table 5. The comparison of theory and experiment at this stage is also shown in figs. 2-5.

To include in our analysis lower energy observables as well, a stronger hypothesis needs to be made: vacuum polarization diagrams are allowed to vary from the SM only in their constant and first derivative terms in a q^2 expansion [21−22]. In such a case, one can, for example, add to the analysis the ratio R_ν of neutral to charged current processes in deep inelastic neutrino scattering on nuclei [26], the "weak charge" Q_W measured in atomic parity violation experiments on Cs [27] and the measurement of g_V/g_A from $\nu_\mu e$ scattering [28]. In this way one obtains the global fit given in the fourth column of table 5 and shown in figs. 2-5. With the progress of LEP the low energy data, while important as a check that no deviations from the expected q^2 dependence arise, play a lesser role in the global fit. Note that the present ambiguity on the value of $\delta\alpha^{-1}(m_Z) = \pm 0.09$ [11] corresponds to an uncertainty on ϵ_3 (the other epsilons are not much affected) given by $\Delta\epsilon_3\ 10^3 = \pm 0.5$ [18]. Thus the theoretical error is still comfortably less than the experimental error.

A number of interesting features are clearly visible from figs.2-5. First, the good agreement with the SM (all the epsilons are within $\lesssim 1\sigma$ from the SM value) and the evidence for weak corrections, measured by the distance of the data from the improved Born approximation point (based on tree level SM plus pure QED or QCD corrections). There is by now a solid evidence for departures from the improved Born approximation where all the epsilons vanish. In other words a clear evidence for the pure weak radiative corrections has been obtained and LEP/SLC are now measuring the various components of these radiative corrections. For example, some authors [29] have studied the sensitivity of the data to a particularly interesting subset of the weak radiative corrections, i.e. the purely bosonic part. These terms arise from virtual exchange of gauge bosons and Higgses. The result is that indeed the measurements are sufficiently precise to require the presence of these contributions in order to fit the data. Second, the general results of the SM fits are reobtained from a different perspective. We see the preference for light Higgs manifested by the tendency for ϵ_3 to be rather on the low side. Since ϵ_3 is practically independent of m_t, its low value demands m_H small. If the Higgs is light then the preferred value of m_t is somewhat lower than the Tevatron result (which in the epsilon analysis is not included among the input data). This is because also the value of $\epsilon_1 \equiv \delta\rho$, which is determined by the widths, in particular by the leptonic whidth, is somewhat low. In particular ϵ_1 increases with m_t and, at fixed m_t, decreases with m_H, so that for small m_H the low central value of ϵ_1 pushes m_t down. Note that also the central value of ϵ_2 is on the low side, because the experimental value of m_W is a little bit too large. Finally, we see that adding the hadronic quantities or the low energy observables hardly makes a difference in the ϵ_i-ϵ_j plots with respect to the case with only the leptonic variables being included (the ellipse denoted by "All Asymm."). But, for example for the ϵ_1-ϵ_3 plot, while the leptonic ellipse contains the same information as one could obtain from a $\sin^2\theta_{eff}$ vs Γ_l plot, the content of the other two ellipses is much larger because it shows that the hadronic as well as the low energy quantities match the leptonic variables without need of any new physics. Note that the experimental values of

ϵ_1 and ϵ_3 in the latter case also depend on the input value of α_s given in eq.(4).

5 The Case for Physics beyond the Standard Model

Given the striking success of the SM why are we not satisfied with that theory? Why not just find the Higgs particle, for completeness, and declare that particle physics is closed? The main reason is that there are strong conceptual indications for physics beyond the SM.

It is considered highly unplausible that the origin of the electro-weak symmetry breaking can be explained by the standard Higgs mechanism, without accompanying new phenomena. New physics should be manifest at energies in the TeV domain. This conclusion follows fron an extrapolation of the SM at very high energies. The computed behaviour of the $SU(3) \otimes SU(2) \otimes U(1)$ couplings with energy clearly points towards the unification of the electro-weak and strong forces (Grand Unified Theories: GUTS) at scales of energy $M_{GUT} \sim 10^{14} - 10^{16}\ GeV$ which are close to the scale of quantum gravity, $M_{Pl} \sim 10^{19}\ GeV$ [30,31]. One can also imagine a unified theory of all interactions also including gravity (at present superstrings [32] provide the best attempt at such a theory). Thus GUTS and the realm of quantum gravity set a very distant energy horizon that modern particle theory cannot anymore ignore. Can the SM without new physics be valid up to such large energies? This appears unlikely because the structure of the SM could not naturally explain the relative smallness of the weak scale of mass, set by the Higgs mechanism at $m \sim 1/\sqrt{G_F} \sim 250\ GeV$ with G_F being the Fermi coupling constant. This so-called hierarchy problem [33] is related to the presence of fundamental scalar fields in the theory with quadratic mass divergences and no protective extra symmetry at m=0. For fermions, first, the divergences are logaritmic and, second, at m=0 an additional symmetry, i.e. chiral symmetry, is restored. Here, when talking of divergences we are not worried of actual infinities. The theory is renormalisable and finite once the dependence on the cut off is absorbed in a redefinition of masses and couplings. Rather the hierarchy problem is one of naturalness. If we consider the cut off as a manifestation of new physics that will modify the theory at large energy scales, then it is relevant to look at the dependence of physical quantities on the cut off and to demand that no unexplained enormously accurate cancellation arise.

According to the above argument the observed value of $m \sim 250\ GeV$ is indicative of the existence of new physics nearby. There are two main possibilities. Either there exist fundamental scalar Higgses but the theory is stabilised by supersymmetry, the boson-fermion symmetry that would downgrade the degree of divergence from quadratic to logarithmic. For approximate supersymmetry the cut off is replaced by the splitting between the normal particles and their supersymmetric partners. Then naturalness demands that this splitting (times the size of the weak gauge coupling) is of the order of the weak scale of mass, i.e. the separation within supermultiplets should be of the order of no more than a few TeV. In this case the masses of most supersymmetric partners of the known particles, a very large managerie of states, would fall, at least in part, in the discovery reach of the LHC. There are consistent, fully formulated field theories constructed on the basis of this idea, the simplest one being the MSSM [34]. Note that all normal observed states are those whose masses are forbidden in the limit of exact $SU(2)\otimes U(1)$. Instead for all SUSY partners the masses are allowed in that limit. Thus when supersymmetry is broken in the TeV range but $SU(2)\otimes U(1)$ is intact only s-partners take mass while all normal particles remain massless. Only at the lower weak scale the masses of ordinary particles are generated. Thus a simple criterium exists to understand the difference between particles and s-particles.

The other main avenue is compositeness of some sort. The Higgs boson is not elementary but either a bound state of fermions or a condensate, due to a new strong force, much stronger than the usual strong interactions, responsible for the attraction. A plethora of new "hadrons", bound by the new strong force would exist in the LHC range. A serious problem for this idea is that nobody sofar has been able to build up a realistic model along these lines, but that could eventually be explained by a lack of ingenuity on the theorists side. The most appealing examples are technicolor theories [23–24]. These models where inspired by the breaking of chiral symmetry in massless QCD induced by quark condensates. In the case of the electroweak breaking new heavy techniquarks must be introduced and the scale analogous to Λ_{QCD} must be about three orders of magnitude larger. The presence of such a large force relatively nearby has a strong tendency to clash with the results of the electroweak precision tests [25].

The hierarchy problem is certainly not the only conceptual problem of the SM. There are many more: the proliferation of parameters, the mysterious pattern of fermion masses and so on. But while most of these problems can be postponed to the final theory that will take over at very large energies, of order M_{GUT} or M_{Pl}, the hierarchy problem arises from the unstability of the low energy theory and requires a solution at relatively low energies.

A supersymmetric extension of the SM provides a way out which is well defined, computable and that preserves all virtues of the SM. The necessary SUSY breaking can be introduced through soft terms that do not spoil the good convergence properties of the theory. Precisely those terms arise from supergravity when it is spontaneoulsly broken in a hidden sector [35]. But alternative mechanisms of SUSY breaking are also being considered [36]. In the most familiar approach SUSY is broken in a hidden sector and the scale of SUSY breaking is very large of order $\Lambda \sim \sqrt{G_F^{-1/2} M_P}$ where M_P is the Planck mass. But since the hidden sector only communicates with the visible sector through gravitational interactions the splitting of the SUSY multiplets is much smaller, in the TeV energy domain, and the Goldstino is practically decoupled. In an alternative scenario the (not so much) hidden sector is connected to the visible one by ordinary gauge interactions. As these are much stronger than the gravitational interactions, Λ can be much smaller, as low as 10-100 TeV. It follows that the Goldstino is very light in these models (with mass of order or below 1 eV typically) and is the lightest, stable SUSY particle, but its couplings are observably large. The radiative decay of the lightest neutralino into the Goldstino leads to detectable photons. The signature of photons comes out naturally in this SUSY breaking pattern: with respect to the MSSM, in the gauge mediated model there are typically more photons and less missing energy. Gravitational and gauge mediation are extreme alternatives: a spectrum of intermediate cases is conceivable. The main appeal of gauge mediated models is a better protection against flavour changing neutral currents. In the gravitational version even if we accept that gravity leads to degenerate scalar masses at a scale near M_{Pl} the running of the masses down to the weak scale can generate mixing induced by the large masses of the third generation fermions [31].

At present the most direct phenomenological evidence in favour of supersymmetry is obtained from the unification of couplings in GUTS. Precise LEP data on $\alpha_s(m_Z)$ and $\sin^2\theta_W$ confirm what was already known with less accuracy: standard one-scale GUTS fail in predicting $\sin^2\theta_W$ given $\alpha_s(m_Z)$ (and $\alpha(m_Z)$) while SUSY GUTS [37] are in agreement with the present, very precise, experimental results. According to the recent analysis of ref.[38], if one starts from the known values of $\sin^2\theta_W$ and $\alpha(m_Z)$, one finds for $\alpha_s(m_Z)$ the results:

$$\begin{aligned} &\alpha_s(m_Z) = 0.073 \pm 0.002 \qquad \text{(Standard GUTS)} \\ &\alpha_s(m_Z) = 0.129 \pm 0.010 \qquad \text{(SUSY GUTS)} \end{aligned} \tag{7}$$

to be compared with the world average experimental value $\alpha_s(m_Z)$ =0.119(4).

Some experimental hints for new physics beyond the SM come from the sky and from cosmology. I refer to solar and atmospheric neutrinos, dark matter and baryogenesis. It seems to me that by now it is difficult to imagine that the neutrino anomalies can all disappear or be explained away [39,40]. Probably they are a manifestation of neutrino oscillations, hence neutrino masses. Massive neutrinos are natural in most GUT's. The see-saw mechanism [41] provides an elegant explanation of the smallness of neutrino masses, inversely proportional to the large scale of L violation. Minimal SU(5) is disfavoured by neutrino masses, because there is no ν_R and B-L is conserved by gauge interactions, while SO(10) provides a very natural context for them [30]. A number of different observations show that most of the matter in the universe is non luminous and that both cold and hot dark matter forms are needed [42]. Neutrinos with a mass of a few eV's could provide the hot dark matter (particles that are relativistic when they drop out of equilibrium). But neutrinos cannot be the totality of dark matter because they are too faintly interacting and have no enough clumping at galactic distances. Cold dark matter particles do not exist in the SM. Plausible candidates are axions or neutralinos. In this respect SUSY in the MSSM version scores a good point while other SUSY options, like the gauge mediated models and the R-parity violating versions, do not offer such a simple possibility. Baryogenesis is interesting because it could occur at the weak scale [43] but not in the SM. For baryogenesis one needs the three famous Sakharov conditions [44]: B violation, CP violation and no termal equilibrium. In principle these conditions could be verified in the SM. B is violated by instantons when kT is of the order of the weak scale (but B-L is conserved). CP is violated by the CKM phase and out of equilibrium conditions could be verified during the electroweak phase transition. So the conditions for baryogenesis appear superficially to be present for it to occur at the weak scale in the SM. However, a more quantitative analysis [45,46] shows that baryogenesis is not possible in the SM because there is not enough CP violation and the phase transition is not sufficiently strong first order, unless $m_H < 40\ GeV$, which is by now excluded by

LEP. Certainly baryogenesis could also occur below the GUT scale, after inflation. But only that part with $|B-L|>0$ would survive and not be erased at the weak scale by instanton effects. Thus baryogenesis at $kT \sim 10^{12}-10^{15}$ GeV needs B-L violation at some stage like for m_ν. The two effects could be related if baryogenesis arises from leptogenesis [48] then converted into baryogenesis by instantons. While baryogenesis at a large energy scale is thus not excluded it is interesting that recent studies have shown that baryogenesis at the weak scale could be possible in the MSSM [47]. In fact, in this model there are additional sources of CP violations and the bound on m_H is modified by a sufficient amount by the presence of scalars with large couplings to the Higgs sector, typically the s-top. What is required is that $m_H \lesssim 80-100$ GeV (in the LEP2 range!), a s-top not heavier than the top quark and, preferentially, a small $\tan\beta$.

6 The Search for the Higgs

The SM works with remarkable accuracy. But the experimental foundation of the SM is not completed if the electroweak symmetry breaking mechanism is not experimentally established. Experiments must decide what is true: the SM Higgs or Higgs plus SUSY or new strong forces and Higgs compositeness.

The theoretical limits on the Higgs mass play an important role in the planning of the experimental strategy. The large experimental value of m_t has important implications on m_H both in the minimal SM [49–51] and in its minimal supersymmetric extension [52,53].

It is well known [49–51] that in the SM with only one Higgs doublet a lower limit on m_H can be derived from the requirement of vacuum stability. The limit is a function of m_t and of the energy scale Λ where the model breaks down and new physics appears. Similarly an upper bound on m_H (with mild dependence on m_t) is obtained [54] from the requirement that up to the scale Λ no Landau pole appears. If one demands vacuum stability up to a very large scale,of the order of M_{GUT} or M_{Pl} then the resulting bound on m_H in the SM with only one Higgs doublet is given by [50]:

$$m_H(GeV) > 138 + 2.1\,[m_t - 175.6] - 3.0\ \frac{\alpha_s(m_Z)-0.119}{0.004}\ . \tag{8}$$

In fact one can show that the discovery of a Higgs particle at LEP2, or $m_H \lesssim 100$ GeV, would imply that the SM breaks down at a scale Λ of the order of a few TeV. Of course, the limit is only valid in the SM with one doublet of Higgses. It is enough to add a second doublet to avoid the lower limit. The upper limit on the Higgs mass in the SM is important for assessing the chances of success of the LHC as an accelerator designed to solve the Higgs problem. The upper limit [54] has been recently reevaluated [55]. For $m_t \sim 175$ GeV one finds $m_H \lesssim 180$ GeV for $\Lambda \sim M_{GUT}-M_{Pl}$ and $m_H \lesssim 0.5-0.8$ TeV for $\Lambda \sim 1$ TeV.

A particularly important example of theory where the bound is violated is the MSSM, which we now discuss. As is well known [34], in the MSSM there are two Higgs doublets, which implies three neutral physical Higgs particles and a pair of charged Higgses. The lightest neutral Higgs, called h, should be lighter than m_Z at tree-level approximation. However, radiative corrections[56] increase the h mass by a term proportional to m_t^4 and logarithmically dependent on the stop mass . Once the radiative corrections are taken into account the h mass still remains rather small: for $m_t = 174$ GeV one finds the limit (for all values of tg β) $m_h < 130$ GeV[53]. Actually there are reasons to expect that m_h is well below the bound. In fact, if h_t is large at the GUT scale, which is suggested by the large observed value ot m_t and by a natural onsetting of the electroweak symmetry breaking induced by m_t, then at low energy a fixed point is reached in the evolution of m_t. The fixed point corresponds to $m_t \sim 195 \sin\beta$ GeV (a good approximate relation for tg $\beta = v_{up}/v_{down} < 10$). If the fixed point situation is realized, then m_h is considerably below the bound, $m_h \lesssim 100\ GeV$[53].

In conclusion, for $m_t \sim 175$ GeV, we have seen that, on the one hand, if a Higgs is found at LEP the SM cannot be valid up to M_{Pl}. On the other hand, if a Higgs is found at LEP, then the MSSM has good chances, because this model would be excluded for $m_h > 130$ GeV.

7 New Physics at HERA?

7.1 Introduction

The HERA experiments H1[57] and ZEUS[58], recently updated in ref.[59], have reported an excess of deep-inelastic e^+p scattering events at large values of $Q^2 \gtrsim 1.5 \times 10^4$ GeV^2, in a domain not previously explored by other experiments. The total e^+p integrated luminosity was of 14.2 +9.5 = 23.7 pb^{-1}, at H1 and of 20.1+13.4 = 33.5 pb^{-1} at ZEUS. The first figure refers to the data before the '97 run[57,58], while the second one refers to part of the continuing '97 run, whose results were presented at the LP'97 Symposium[59]. Both experiments collected in the past about 1 pb^{-1} each with an e^- beam. A very schematic description of the situation is as follows. At $Q^2 \gtrsim 15\ 10^4$ in the neutral current channel (NC), H1 observes 12+6 = 18 events while about 5+3 = 8 were expected and ZEUS observes 12 + 6 = 18 events with about 9 + 6 =15 expected. In the charged current channel (CC), in the same range of Q^2, H1 observes 4+2 = 6 events while about 1.8+1.2 = 3 were expected and ZEUS observes 3 + 2 = 5 events with about 1.2 + 0.8 = 2 expected. The distribution of the first H1 data suggested a resonance in the NC channel. In the interval $187.5 < M < 212.5\ GeV$, which corresponds to $x \simeq 0.4$, and $y > 0.4$, H1 in total finds 7 + 1 = 8 events with about 1 + 0.5 = 1.5 expected. But in correspondence of the H1 peak ZEUS observes a total of 3 events, just about the number of expected events. In the domain $x > 0.55$ and $y > 0.25$ ZEUS observes 3 + 2 events with about 1.2 + 0.8 = 2 expected. But in the same domain H1 observes only 1 event in total more or less as expected.

We see that with new statistics the evidence for the signal remain meager. The bad features of the original data did not improve. First, there is a problem of rates. With more integrated luminosity than for H1, ZEUS sees about the same number of events in both the NC and CC channels. Second, H1 is suggestive of a resonance (although the evidence is now less than it was) while ZEUS indicates a large x continuum (here also the new data are not more encouraging). The difference could in part, but apparently not completely [60], be due to the different methods of mass reconstruction used by the two experiments, or to fluctuations in the event characteristics. Of course, at this stage, due to the limited statistics, one cannot exclude the possibility that the whole effect is a statistical fluctuation. All these issues will hopefully be clarified by the continuation of data taking. Meanwhile, it is important to explore possible interpretations of the signal, in particular with the aim of identifying additional signatures that might eventually be able to discriminate between different explanations of the reported excess.

7.2 Structure Functions

Since the observed excess is with respect to the SM expectation based on the QCD-improved parton model, the first question is whether the effect could be explained by some inadequacy of the conventional analysis without invoking new physics beyond the SM. In the somewhat analogous case of the apparent excess of jet production at large transverse energy E_T recently observed by the CDF collaboration at the Tevatron [61], it has been argued [62] that a substantial decrease in the discrepancy can be obtained by modifying the gluon parton density at large values of x where it has not been measured directly. New results [63] on large p_T photons appear to cast doubts on this explanation because these data support the old gluon density and not the newly proposed one. In the HERA case, a similar explanation appears impossible, at least for the H1 data. Here quark densities are involved and they are well known at the same x but smaller Q^2 [64,65], and indeed the theory fits the data well there. Since the QCD evolution is believed to be safe in the relevant region of x, the proposed strategy is to have a new component in the quark densities at very large x, beyond the measured region, and small Q^2 which is driven at smaller x by the evolution and contributes to HERA when Q^2 is sufficiently large [64]. However it turns out that a large enough effect is only conceivable at very large x, $x \gtrsim 0.75$, which is too large even for ZEUS. The compatibility with the Tevatron is also an important constraint. This is because ep scattering is linear in the quark densities, while $p\bar{p}$ is quadratic, so that a factor of 1.5-2 at HERA implies a large effect also at the Tevatron. In addition, many possibilities including intrinsic charm [66] (unless $\bar{c} \neq c$ at the relevant x values [67]) are excluded from the HERA data in the CC channel [68]. More in general, if only one type of density is modified, then in the CC channel one obtains too large an effect in the $\bar{u}$ and d cases and no effect at all in the $\bar{d}$ and u cases [68]. In conclusion, it is a fact that nobody sofar was able to even roughly fit the data. This possibility is to be kept in mind if eventually the data will drift towards the SM and only a small excess at particularly large x and Q^2 is left in NC channel.

7.3 Contact Terms

Still considering the possibility that the observed excess is a non-resonant continuum, a rather general approach in terms of new physics is to interpret the HERA excess as due

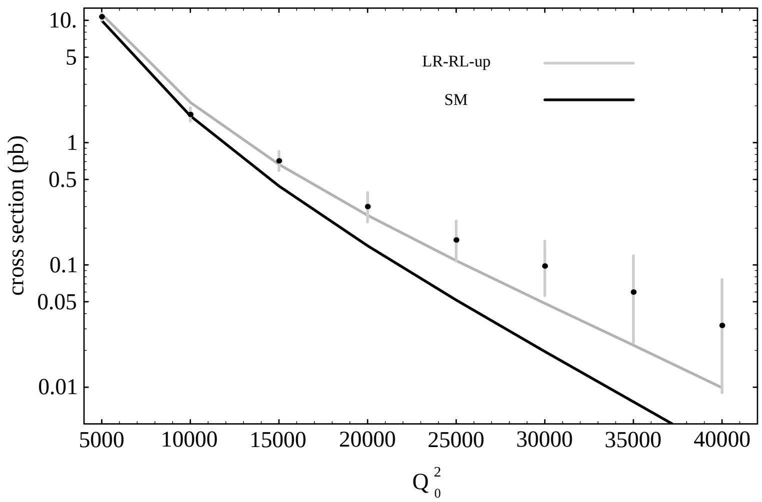

Figure 6: Example of a fit to the HERA data presented at LP'97 from a LR+RL contact term with only u-quarks [78] .

to an effective four-fermion $\bar{e}e\bar{q}q$ contact interaction [69] with a scale Λ of order a few TeV. It is interesting that a similar contact term of the $\bar{q}q\bar{q}q$ type, with a scale of exactly the same order of magnitude, could also reproduce the CDF excess in jet production at large E_T [61]. (Note, however, that this interpretation is not strengthened by more recent data on the dijet angular distribution [70]). One has studied in detail [71,72] vector contact terms of the general form

$$\Delta L = \frac{4\pi\eta_{ij}}{(\Lambda^{\eta}_{ij})^2}\ \bar{e}_i\gamma^\mu e_i\ \bar{q}_j\gamma_\mu q_j. \tag{9}$$

with $i,j = L,R$ and η a $\pm$ sign. Strong limits on these contact terms are provided by LEP2 [73] (LEP1 limits also have been considered but are less constraining [74]), Tevatron [75] and atomic parity violation (APV) experiments [27]. The constraints are even more stringent for scalar or tensor contact terms. APV limits essentially exclude all relevant A_eV_q component. The CDF limits on Drell-Yan production are particularly constraining. Data exist both for electron and muon pairs up to pair masses of about 500 GeV and show a remarkable $e-\mu$ universality and agreement with the SM. New LEP limits (especially from LEP2) have been presented [73]. In general it would be possible to obtain a reasonably good fit of the HERA data, consistent with the APV and the LEP limits, if one could skip the CDF limits [76]. But, for example, a parity conserving combination $(\bar{e}_L\gamma^\mu e_L)(\bar{u}_R\gamma_\mu u_R)+(\bar{e}_R\gamma^\mu e_R)(\bar{u}_L\gamma_\mu u_L)$ with $\Lambda^+_{LR} = \Lambda^+_{RL} \sim 4$ TeV still leads to a marginal fit to the HERA data and is compatible with all existing limits [76,77] (see fig.6 [78]). Because we expect contact terms to satisfy $SU(2)\bigotimes U(1)$, because they reflect physics at large energy scales, the above phenomenological form is to be modified into $\bar{L}_L\gamma_\mu L_L(\bar{u}_R\gamma^\mu u_R + \bar{d}_R\gamma^\mu d_R) + \bar{e}_R\gamma_\mu e_R\bar{Q}_L\gamma^\mu Q_L)$, where L and Q are doublets [79]. This form is both gauge invariant and parity conserving. Here one has taken into account the requirement that contact terms corresponding to CC are too constrained to appear. More sophisticated fits have also been performed [76].

In conclusion, contact terms are severely constrained but not excluded. The problem of generating the phenomenologically required contact terms from some form of new physics at larger energies is far from trivial [79,80]. Note also that contact terms require values of $g^2/\Lambda^2 \sim 4\pi/(3-4\ \text{TeV})^2$, which would imply a very strong nearby interaction. Indeed for g^2 of the order of the $SU(3)\bigotimes SU(2)\bigotimes U(1)$ couplings, Λ would fall below 1 TeV, where the contact term description is inadequate. We recall that the effects of contact terms should be present in both the e^+ and the e^- cases with comparable intensity. Definitely contact terms cannot produce a CC signal [81], as we shall see, and no events with isolated muons and missing energy.

7.4 Leptoquarks

I now focus on the possibility of a resonance with e^+q quantum numbers, namely a leptoquark [71,82,83,84,85,86,87], of mass $M \sim 190-210\ GeV$, according to H1. The most obvious possibility is that the production at HERA occurs from valence u or d quarks, since otherwise the coupling would need to be quite larger, and more difficult to reconcile with existing limits. However production from the sea is also considered. Assuming an S-wave state, one may have either a scalar or a vector leptoquark. I only consider here the first option, because vector leptoquarks are more difficult to reconcile with their apparent absence at the Tevatron. The coupling λ for a scalar ϕ is defined by $\lambda\phi\bar{e}_L q_R$ or $\lambda\phi\bar{e}_R q_L$, The corresponding width is given by $\Gamma = \lambda^2 M_\phi/16\pi$, and the production cross section on a free quark is given in lowest order by $\sigma\ =\ \frac{\pi}{4s}\lambda^2$.

Including also the new '97 run results, the combined H1 and ZEUS data, interpreted in terms of scalar leptoquarks lead to the following list of couplings [89,71,88]:

$$e^+u \to \lambda\sqrt{B} \sim 0.017-0.025; \quad e^+d \to \lambda\sqrt{B} \sim 0.025-0.033; \quad e^+s \to \lambda\sqrt{B} \sim 0.15-0.25 \tag{10}$$

where B is the branching ratio into the e-q mode. By s the strange sea is meant. For comparison note that the electric charge is $e = \sqrt{4\pi\alpha} \sim 0.3$. Production via $e^+\bar{u}$ or $e^+\bar{d}$ is excluded by the fact that in these cases the production in e^-u or e^-d would be so copious that it should have shown up in the small luminosity already collected in the e^-p mode. The estimate of λ in the strange sea case is merely indicative due to the large uncertainties on the value of the small sea densities at the relatively large values relevant to the HERA data. The width is in all cases narrow: for $B \sim 1/2$ we have $\Gamma \sim 4-16\ MeV$ for valence and $350-1000\ MeV$ for sea densities.

It is important to notice that improved data from the CDF and D0 [63] on one side and from APV [27] and LEP [73] on the other considerably reduce the window for leptoquarks. Consistency with the Tevatron, where scalar leptoquarks are produced via model-independent (and λ-independent) QCD processes with potentially large rates, demands a value of B sizeably smaller than 1. In fact, the most recent NLO estimates of the squark and leptoquark production cross sections [90,91] allow to estimate that at 200 GeV approximately 6–7 events with e^+e^-jj final states should be present in the combined CDF and D0 data sets. For

$B = 1$ the CDF limit is 210 GeV, the latest D0 limit is 225 GeV at 95%CL. The combined CDF+D0 limit is 240 GeV at 95%CL [63]. We see that for consistency one should impose:

$$B \lesssim 0.5 - 0.7 \tag{11}$$

Finally, the case of a 200 GeV vector leptoquark is most likely totally ruled out by the Tevatron data, since the production rate can be as much as a factor of 10 larger than that of scalar leptoquarks.

There are also lower limits on B, different for production off valence or sea quarks, so that only a definite window for B is left in all cases. For production off valence the limit arises from APV [27], while for the sea case it is obtained from recent LEP2 data [73].

One obtains a limit from APV because the s-channel echange amplitude for a leptoquark is equivalent at low energies to an $(\bar{e}q)(\bar{q}e)$ contact term with amplitude proportional to λ^2/M^2. After Fierz rearrangement a component on the relevant APV amplitude $A_e V_q$ is generated, hence the limit on λ. The results are [81]

$$e^+u \to \lambda \lesssim 0.058; \quad e^+d \to \lambda \lesssim 0.055 \tag{12}$$

The above limits are for $M = 200\ GeV$ (they scale in proportion to M) and are obtained from the quoted error on the new APV measurement on Cs. This error being mainly theoretical, one could perhaps take a more conservative attitude and somewhat relax the limit. Comparing with the values for $\lambda\sqrt{B}$ indicated by HERA, given in eq.(10), one obtains lower limits on B:

$$e^+u \to B \gtrsim 0.1 - 0.2; \qquad e^+d \to B \gtrsim 0.2 - 0.4 \tag{13}$$

For production off the strange sea quark the upper limit on λ is obtained from LEP2 [73], in that the t-channel exchange of the leptoquark contributes to the process $e^+e^- \to s\bar{s}$ (similar limits for valence quarks are not sufficiently constraining, because the values of λ required by HERA are considerably smaller). Recently new results have been presented by ALEPH, DELPHI and OPAL [73]. The best limits are around $\lambda \lesssim 0.6 - 0.7$ This, given eq.(10), corresponds to

$$e^+s \to B \gtrsim 0.05 - 0.2 \tag{14}$$

Recalling the Tevatron upper limits on B, given in eq.(11), we see that only a definite window for B is left in all cases.

Note that one given leptoquark cannot be present both in e^+p and in e^-p (unless it is produced from strange quarks).

7.5 S-quarks with R-parity Violation

I now consider specifically leptoquarks and SUSY [93,94,95,96,97,71]. In general, in SUSY one could consider leptoquark models without R-parity violation. It is sufficient to introduce together with scalar leptoquarks also the associated spin-1/2 leptoquarkinos [92]. In this way one has not to give up the possibility that neutralinos provide the necessary cold dark matter in the universe. We find it more attractive to embed a hypothetical leptoquark in the minimal supersymmetric extension of the Standard Model [34] with violation of R parity [98]. The connection with the HERA events has been more recently invoked in ref. [96]. The corresponding superpotential can be written in the form

$$W_R \equiv \mu_i H L_i + \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k \ , \tag{15}$$

where $H, L_i, E^c_j, Q_k, (U,D)^c_l$ denote superfields for the $Y = 1/2$ Higgs doublet, left-handed lepton doublets, lepton singlets, left-handed quark doublets and quark singlets, respectively. The indices i, j, k label the three generations of quarks and leptons. Furthermore, we assume the absence of the λ'' couplings, so as to avoid rapid baryon decay, and the λ couplings are not directly relevant in the following.

The squark production mechanisms permitted by the λ' couplings in (15) include e^+d collisions to form $\tilde{u}_L, \tilde{c}_L$ or $\tilde{t}_L$, which involve valence d quarks, and various collisions of the types e^+d_i $(i = 2,3)$ or $e^+\bar{u}_i$ $(i = 1,2,3)$ which involve sea quarks. A careful analysis leads to the result that the only processes that survive after taking into account existing low energy limits are

$$e^+_R d_R \rightarrow \tilde{c}_L; \quad e^+_R d_R \rightarrow \tilde{t}_L; \quad e^+_R s_R \rightarrow \tilde{t}_L \tag{16}$$

For example $e^+_R d_R \rightarrow \tilde{u}_L$ is forbidden by data on neutrinoless double beta decay which imply [99]

$$|\lambda'_{111}| < 7 \times 10^{-3} \left(\frac{m_{\tilde{q}}}{200 \text{ GeV}}\right)^2 \left(\frac{m_{\tilde{g}}}{1 \text{ TeV}}\right)^{\frac{1}{2}} \ . \tag{17}$$

where $m_{\tilde{q}}$ is the mass of the lighter of $\tilde{u}_L$ and $\tilde{d}_R$, and $m_{\tilde{g}}$ is the gluino mass.

It is interesting to note [94] that the left s-top could be a superposition of two mass eigenstates $\tilde{t}_1, \tilde{t}_2$, with a difference of mass that can be large as it is proportional to m_t:

$$\tilde{t}_L = \cos\theta_t \ \tilde{t}_1 \ + \ \sin\theta_t \ \tilde{t}_2 \tag{18}$$

where θ_t is the mixing angle. With $m_1 \sim 200 \ GeV$, $m_2 \sim 230 \ GeV$ and $\sin^2\theta_t \sim 2/3$ one can obtain a broad mass distribution, more similar to the combined H1 and ZEUS data. (But with the present data one has to swallow that H1 only observes $\tilde{t}_1$ while ZEUS only sees $\tilde{t}_2$!). However, the presence of two light leptoquarks makes the APV limit more stringent. In fact it becomes

$$B < B_\infty[1 + \tan^2\theta_t \frac{m_1^2}{m_2^2}] \tag{19}$$

Thus, for the above mass and mixing choices, the above quoted APV limit B_∞ must be relaxed invoking a larger theoretical uncertainty on the Cs measurement.

Let us now discuss [71] if it is reasonable to expect that $\tilde{c}$ and $\tilde{t}$ decay satisfy the bounds on the branching ratio B. A virtue of s-quarks as leptoquark is that competition of R-violating and normal decays ensures that in general $B < 1$.

In the case of $\tilde{c}_L$, the most important possible decay modes are the R-conserving $\tilde{c}_L \to c\chi_i^0$ $(i = 1,..,4)$ and $\tilde{c}_L \to s\chi_j^+$ $(j = 1, 2)$, and the R-violating $\tilde{c}_L \to de^+$, where χ_i^0, χ_j^+ denote neutralinos and charginos, respectively. In this case it has been shown that, if one assumes that $m_{\chi_j^+} > 200$ GeV, then , in a sizeable domain of the parameter space, the neutralino mode can be sufficiently suppressed so that $B \sim 1/2$ as required (for example, the couplings of a higgsino-like neutralino are suppressed by the small charm mass).

In the case of $\tilde{t}_L$, it is interesting to notice that the neutralino decay mode $\tilde{t}_L \to t\chi_i^0$ is kinematically closed in a natural way. In order to obtain a large value of B in the case of s-top production off d-quarks, in spite of the small value of λ, it is sufficient to require that all charginos are heavy enough to forbid the decay $\tilde{t}_L \to b\chi_j^+$. However, we do not really want to obtain B too close to 1, so that in this case some amount of fine tuning is required. Or, with charginos heavy, one could invoke other decay channels as, for example, $\tilde{t} \to \tilde{b}W^+$ [102]. But the large splitting needed between $\tilde{t}$ and $\tilde{b}$ implies problems with the ρ-parameter of electroweak precision tests, unless large mixings in both the s-top and s-bottom sectors are involved and their values suitably chosen. To obtain $B \sim 1/2$ is more natural in the case of s-top production off s-quarks, because of the larger value of λ, which is of the order of the gauge couplings.

The interpretation of HERA events in terms of s-quarks with R-parity violation requires a very peculiar family and flavour structure [100]. The flavour problem is that there are very strong limits on products of couplings from absence of FCNC. The unification problem is that nucleon stability poses even stronger limits on products of λ couplings that differ by the exchange of quarks and leptons which are treated on the same footing in GUTS. However it was found that the unification problem can be solved and the required pattern can be embedded in a grand unification framework [100]. The already intricated problem of the mysterious texture of masses and couplings is however terribly enhanced in these scenarios.

7.6 Charged Current Events

We have mentioned that in the CC channel at $Q^2 \gtrsim 15\ 10^4$ H1 and ZEUS see a total of 11 events with 5 expected. The statistics is even more limited than in the NC case, so one cannot at the moment derive any firm conclusion on the existence and on the nature of an excess in that channel. However, the presence or absence of a simultaneous CC signal is extremely significant for the identification of the underlying new physics (as it would also be the case for the result of a comparable run with an e^- beam, which however is further away in time). It is found that in most of the cases the CC signal is not expected to arise [81,101,103,102]. But if it is present at a comparable rate as for the NC signal, the corresponding indications are very selective. In fact the following results are found. Due to the existing limits on charged current processes, it is not possible to find a set of contact terms that satisfy $SU(2) \bigotimes U(1)$ invariance and lead to a significant production of CC events. For leptoquarks, we recall that a leptoquark with branching ratio equal to 1 in e^+q is excluded by the recent Tevatron limits. Therefore on one hand some branching fraction in the CC channel is needed. On the other hand, one finds that there is limited space for the possibility that a leptoquark can generate a CC signal at HERA with one single parton quark in the final state. This occurrence would indicate $SU(2) \bigotimes U(1)$ violating couplings or couplings to a current containing the charm quark. A few mechanisms for producing CC final states from $\tilde{c}$ or $\tilde{t}$ have been proposed [81,103]. In all cases $\tilde{c}$ or $\tilde{t}$ lead to multiparton final states. Since apparently the CC candidates are all with one single jet, some strict requirements on the masses of the partecipating particles must be imposed so that some partons are too soft to be visible while others coelesce into a single visible jet. So, s-quarks with R-parity violating decays could indeed produce CC events or events with charged leptons and missing energy. But the observation of such events would make the model much more constrained.

8 Conclusion

The HERA anomaly is an interesting feature that deserves further attention and more experimental effort. But at the moment it does not represent a convincing evidence of new physics. The same is true for the other few possible discrepancies observed here and there in the data. The overall picture remains in impressive agreement with the SM. Yet, for conceptual reasons, we remain confident that new physics will eventually appear at the LHC if not before.

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